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CONSTRUCTAL DESIGN OF LATENT HEAT STORAGE SYSTEMS

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1. INTRODUCTION

The project applies constructal theory to enhance the design of heat-flow paths in latent heat storage systems, aiming to minimize the time required for complete melting of the material. Constructal theory suggests that optimal flow configurations, which can be achieved by allowing more degrees of freedom in the design, facilitate better flow access.

2. OBJECTIVES

The main goal is to find effective 2D and 3D heat-flow architectures that lead to the fastest melting process. Starting with a simple structure where a single line acts as the heat source, the design evolves by allowing the heat source to change shape. Numerical simulations are used to identify geometric features that result in the fastest melting process.

3. METHODS

The study uses numerical simulations to explore the layout of invading lines that minimize melting time. By increasing the freedom to morph the flow architecture, a steeper S-shaped melting fraction curve is achieved. Parameters such as the number of bifurcation levels, stem length, bifurcation angle, and Peclet number are varied to optimize the melting fraction curve.

4. RESULTS

The results show that increasing the complexity and degrees of freedom of the structure enhances the heat transfer rate density. The angles between heat invasion lines have a minor effect compared to other factors like the number of branching levels, stem length, and branch lengths. The impact of natural convection in the melt zone is also documented.

5. CONCLUSION

The Constructal Law provides valuable insights into optimizing flow systems across various disciplines. The studies and numerical simulations demonstrate the versatility and significance of this principle in driving innovation and improving system efficiency.

6. ADDITIONAL INSIGHTS

- The study identifies two phases in the melting process: "invasion" (heat diffuses along the line) and "consolidation" (heat diffuses perpendicularly).
- The evolution of the melt layer is analyzed in both 2D and 3D contexts, with the amount of melted material following an S-shaped curve.

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- Faster diffusion occurs with more complex designs, steepening the S-curve.
- The article reviews traditional designs and introduces tree-shaped surfaces for volumetric heating and cooling.
- The challenge is to configure the heating paths to accelerate the energy storage process.

6.1. **Tree Invasion**

The natural tendency of flow systems that are free to morph is to develop configurations that provide greater access to the currents that flow. In the case of storage by melting, the flow is of heat from the invading plate to the rest of the domain, which is solid at the melting temperature. The invading plate is given the freedom to change its shape as it grows, leading to tree-shaped paths with more levels of bifurcation.

6.2. **3D Configuration**

In a three-dimensional geometry, the invading line of higher temperature is a thin needle. Melting occurs around the needle as it invades the solid. The scales of the S-history change if the spreading is from one point to a volume, instead of from one point to an area.

This summary encapsulates the essence of the project, highlighting the application of constructal theory to optimize heat-flow paths for efficient energy storage through melting. The detailed exploration of various parameters and the introduction of tree-shaped paths underscore the innovative approach taken in this study.

6.3. **Constructal Law and Flow Systems**

The constructal law describes how systems evolve to improve flow access, often resulting in tree-like structures that enhance the movement of currents. This principle is applied to energy storage systems to optimize heat transfer during the melting process of PCM.

6.4. **Melting Process in PCM**

The study examines the melting of PCM within a square domain, heated by an invading line at a higher temperature. The amount of melted material follows an S-shaped curve over time. Unlike previous studies with fixed heating patterns, this study allows the pattern to change freely, leading to the discovery of tree-like designs that improve heat spread and melting efficiency.

6.5. **Numerical Simulations and Results**

- The domain is a square filled with PCM solid at 303 K, with an adiabatic outer surface.
- Heat is introduced through an invading line at 353 K, which can branch out and advance.
- The heat conduction in the liquid PCM follows the energy equation, and the properties are assumed to be the same in liquid and solid states.
- The study finds that the melt layer thickness during invasion has a parabolic shape in time, and the instantaneous enclosed area is proportional to time.
- The growth of melted material during consolidation is slower than during invasion, explaining the inflexion of the S-curve.
- Numerical simulations validate the theoretical results, showing that tree-shaped invading lines accelerate the approach to complete melting along a steeper S-curve.

6.6. **Effect of Complexity and Stem Length**

- The effect of complexity (number of bifurcation levels) on the evolution of the average temperature is assessed.
- Trees with greater levels of complexity accelerate the arrival of equilibrium.

- The optimal stem length is found to be around 0.6 times the length of the domain.
- The study explores whether the melting process can be further accelerated by varying the stem length and bifurcation angle.

6.7. **Optimal Configuration**

- The simulations aim to find the optimal configuration for the shortest melting duration.
- The results show that a bifurcation angle of 150 degrees and a minimum stem length of 0.1 times the domain length yield the shortest melting duration.
- Freely varying bifurcation angles accelerate the melting process.

6.8. **Peclet Number and Melting Process**

- The rate of melting depends on the Peclet number, which is the ratio of the time of thermal diffusion perpendicular to the invading line divided by the time of line invasion.
- Higher Peclet numbers and optimal branching designs accelerate the melting process.
- The study compares one-line invasion at high Peclet numbers with optimized Y-shaped invasion at lower Peclet numbers, showing that morphing the design can significantly speed up the melting process.

6.9. **Conclusions**

The paper investigates the numerical process of phase-change energy storage, focusing on how the layout of higher temperature lines, which can morph freely, affects the melting process. The results show that allowing more freedom for the flow architecture to morph results in a steeper S curve, indicating faster melting. Key parameters like the number of bifurcation levels, stem length, bifurcation angle, and Peclet number were analyzed, with the conclusion that more design flexibility leads to better performance.

This summary encapsulates the key findings and methodologies of the study, highlighting the application of constructal theory to optimize heat-flow paths for efficient energy storage through melting. The detailed exploration of various parameters and the introduction of tree-shaped paths underscore the innovative approach taken in this research.

The study describes a two-dimensional square domain filled with a solid at its melting temperature (Tm). At time t = 0, a plate at a higher temperature (Tm+ΔT) starts growing along the centerline from x = 0 to x = L at a constant speed (V). Liquid layers of thickness δ(x) form on both sides of the advancing line. The thickness δ is determined by balancing the conduction heat flux (q'') into the melting front and the rate of melting at the front.

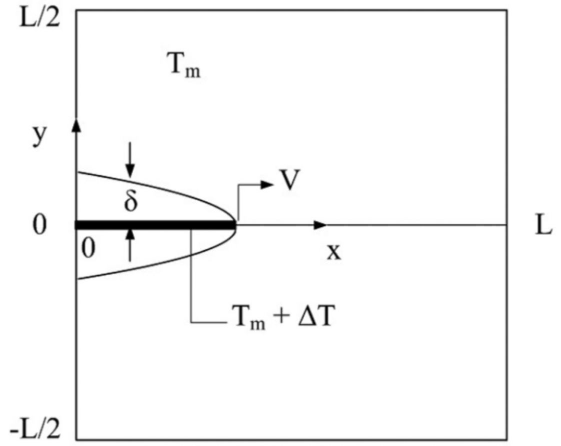

Fig. 1 – Square shaped construct containing the line-shaped invasion advancing.

Tree Invasion. The natural tendency of all flow systems that are free to morph is to develop configurations that provide greater access to the currents that flow. In the case of storage by melting, the flow is of heat, from the invading plate to the rest of the domain, which is solid at T_m. In this section, we endow the invading plate with freedom to change its shape as it grows. The change is from the single line to the tree-shaped paths. More freedom means more levels of bifurcation (n) in the invading tree of plates. Relative to Fig. 2, the single-plate invasion scenario of Fig. 1 is the tree with one stem and no branches (n = 0).

For analytical ease, consider the limit where the invading finger of melt is slender enough so that the melt generated during invasion is small in comparison with the melt generated during consolidation. This is the limit of slender melt layers on both sides of the invading plate, which is represented by $\left(\frac{a}{LV}\right) \ll 1,$

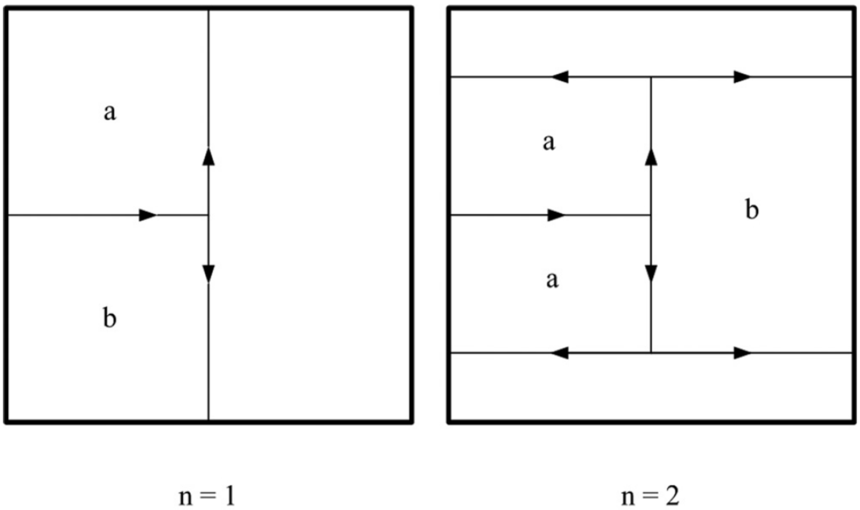

Fig. 2 – Two-dimensional model of a tree-shaped line invasion of a conducting domain for one and two levels of bifurcation.

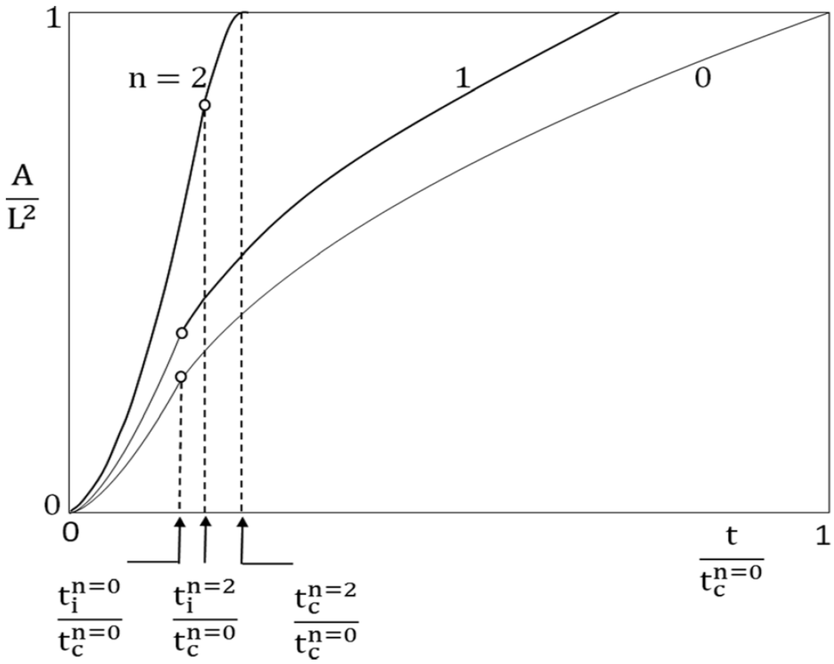

Fig. 3 – The effect of the number of the bifurcation levels on the shape of the S-curve.